A NOVEL LABORATORY TEST METHOD TO MEASURE DYNAMIC WATER PRESSURE UNDERNEATH A CRACKED CONCRETE PAVEMENT

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Abstract

Water infiltration through a discontinuity (crack/joint) in a pavement generates water pressure at the end of the discontinuity when experience traffic load. If this discontinuity extends to the full depth, the generated water pressure can lead to deterioration of foundation material, which ultimately can create under stab voids resulting poor load transfer efficiency and failure of the pavement. A novel laboratory test has been developed to measure water pressure underneath a flooded concrete slab that contains 2mm continuous pore across the full depth. The slab was subjected to dynamic load of a 5kN and 10kN, applied at four different frequencies, 1Hz, 5Hz, 10Hz and 15Hz. Excellent repeatability has been achieved on measuring pore water pressure. The results also showed that pore water pressure increases with increasing load frequency, but the influence of load magnitude and the depth of surface water was found to have only marginal impact.

Key words: Concrete pavement, water pressure; dynamic loading; water depth.

1. Introduction

Despite good service history, both asphalt and concrete pavement often suffer from the deterioration due to water ingress through joints or cracks. The negative impact of water on pavement performance is a well-known concern among pavement engineering community (Dong et al 2008). Water stagnation on the pavement surface after a prolong rainy period or poor drainage develops ponding. The stagnated water penetrates through the cracks/joint and develop pore water pressure under the influence of traffic loading. It is generally believed that the water on the surface or water build up inside the pavement exacerbates due to dynamic load (Garg et al, 2004, Karlson, 2005; Kim, Lutif, Bhasin and Little, 2008; Lindly, Jay K., Elsayed,Ashraf S., 1995; Willway, Baldachin, Reeves, and Harding, 2008, Cerezo et al, 2014). Water ingress accelerates pavement deterioration which lead to pumping under the effect of pressure, particularly in conditions of high vehicle speeds and heavy traffic loads. Pumping can be happened at cracks as well as joint, which can significantly reduce pavement performance. Figure 1 shows a schematic representation of tyre-water-pavement interaction and pore water pressure build up at the fine crack.

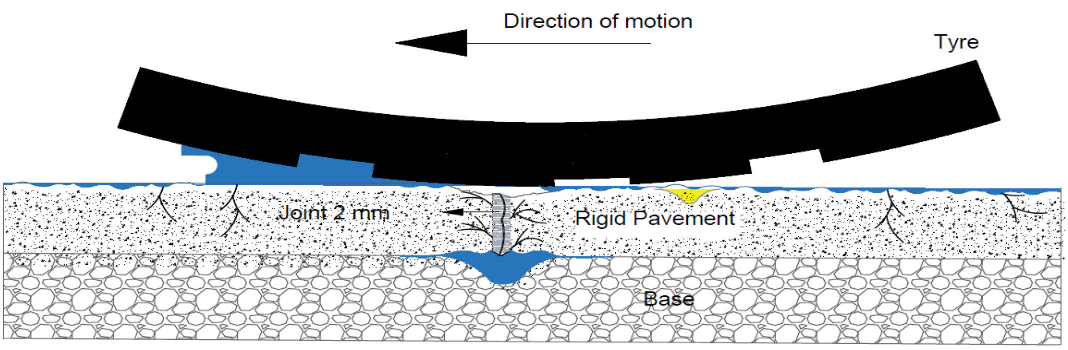


Figure 1. Gap under the joint due to dynamic pressure

As shown in Figure 1, water ingress through cracks gradually deteriorate surrounding material and reduces load transfer across the cracks. In addition, Ridgeway (1982) reported that excess pore water pressure can be formed inside the subgrade and pavement structural components by tyre influences. Over a long period of time, and under repeated loading, materials under the slab gradually erode, which ultimately increase moisture content and creates voids under the slab. High moisture content has a considerable negative influence on road base and subgrade materials.

Since the fundamental requirement of a slab is to spread the imposed wheel load evenly throughout the foundation, any voiding and moisture content, however small, has a detrimental effect on the performance of a pavement (Moulton, 1980). When voids develop beneath a slab, slabs are likely to crack due to fatigue and/or settlement.

Although there have been several studies on water pressure in pavement, most of them are computational and /or analytical. Experimental research is very limited due to the complexity of simulating actual tyre-water-pavement interaction in the laboratory condition let alone measuring actual pressure in the field. To simulate tyre-water-pavement interaction, the notable experimental research was conducted by Jiang et al. (2013) by created dynamic water pressure in a cylindrical asphalt concrete sample with compressed air. The sample base was wrapped with epoxy resin to orient the flow of water through voids in the specimen into an established space. It was indicated that dynamic water pressure on asphalt surface depends on the load magnitude. The excess water pressure decreases the frictional strength of the structural part of the road and foundation materials by generating buoyancy inside these materials (Cook and Dykins, 1991; Kutay and Aydilek, 2007). However, none of the above studies investigated how much water pressure build up when pavement flooded with water.

2. Objectives

This study concentrates on developing a laboratory test method to simulate tyre-water-pavement interaction for the pore water pressure measurement under a repeated vertical load when pavement surface is subjected to flooding with various depths of water. A detail description of the test development and experimental procedure are given. The repeatability and reproducibility of the test are explained. In addition, the experiments are expended to investigate the influence of load magnitude, load frequency, tyre tread shape, and patterns, and depth of surface water are investigated.

3. Test Development

As previously mentioned, simulating tyre pavement interaction and related water pressure measurement in real pavement and even in the laboratory environment is extremely difficult due to the complexity of tyre interaction with the pavement structure, material variability and influence of other factors such as layer deboning, vehicle speed, tread shape and pattern, for example. Therefore, a significant part of the investigation has been dedicated for the development of a laboratory test method simulative to actual tyre-water-pavement interaction. Careful considerations are given to design an idealised pavement section, load platen, tread characterises and test parameters. A brief explanation of these parameters is given in the following sections.

3.1. Idealised pavement section

Concrete slab (300mm x 300mm x 100mm) was manufactured to represent a typical pavement section. The slab had a 150mm x 150mm x 20mm deep recess at the middle. This recess was used to fill with 1mm to 2mm water to measure water pressure. A 12mm plywood foundation with dimensions 440x385mm was fixed under the plastic container, to avoid water splash and to provide rigidity. A 40mm rubber base layer was placed at the bottom of the slab to simulate a typical subgrade This rubber base was originally a rubber tile that is used to tile children’s playgrounds as it is ideal to absorb the impact and prevent injuries from occurring when a child falls off. The 40mm version which was the thickest available from the supplier who states that it can absorb the impact of a child from a height of 1.87 metres, and it complies with BS EN 1177. So, the fulfilment of this parameter made it ideal for this experiment as it can then absorb the impact during the testing process and replicate a soft subgrade. Furthermore, as the rubber layer on the bottom was designed intending to act as impermeable strata as shown in figure 1.

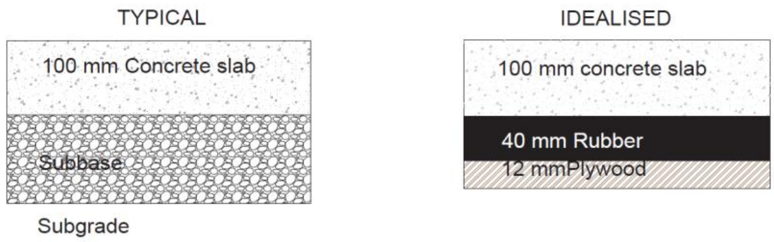
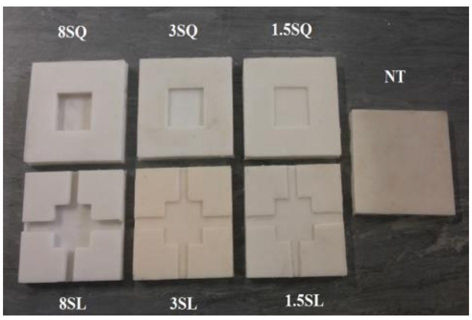


Figure 2: typical and idealised concrete pavement Section

3.2. Load platen and tread characteristics

The dimension of the loading platen was based on the concept that a truck tyre patch is approximately 300 mm in diameter; consequently, this was scaled down three times to 100mm. To keep manufacturing process simple, a square shape was adopted. A 12mm rubber pad was attached to the loading platen by adhesive. The rubber pad contained two simple thread shape and pattern**-** a square slot and a square slot with a channel. The reasoning behind this adaptation is briefly explained below;

Basically, there are four primary types of tyre tread, namely, symmetrical, directional, asymmetrical, and directional asymmetrical these characterised by the geometrical shape of the grooves, ribs, sipes, dimples, blocks and shoulder. The detail explanation of each tyre type, advantage, and limitations can be found in the literature (Heisler 2002; Hanson et al. 2004; Gent and Walter 2006; Bodziak 2008; McDonald 1992, Rahman and Thom 2012). It is evident that the actual tread shape and pattern in real tyre is complex, however, most tyres tread have two general characteristics in common. The first one is a channel to remove water quickly from the contact area (act like a water channel to avoid aqua planning) and the second one is a rain groove (voids to ensure traction) to pump water out from under the tyre by the action of the tread flexing. However, under dynamic loading, the characteristics of these elements interact and there is a combination of pumping, and splashing happen at the same time. It was therefore decided to keep thread pattern simple to so that a clear demarcation between two patterns can be identified. Figures 3a and 3b show the thread pattern and loading platen respectively.



a) Rubber pad representing tread pattern and shape

b) The setup on concrete pavement, load device and rubber

Figure 3 treads shapes and pattern Load device

The following tread characteristics are chosen for this investigation:

- Tread depth: Tread depth: 8mm tread depth to represent new tyre, 3mm to represent part worn tyre and 1.5mm to represent worn tyre.

- Tread pattern: a squared box (SQ) to simulate Sipes, groove and dimple of the tyre and a square box with a channel (SL) to represent block and ribs of the tyre and non-treaded tyres (NT).

4. Test Set-up and Data acquisition

A 2mm pore hole was created at the centre of the recess to representative a continuous void through the depth in the 150mm x 150mm x 20mm recessed area (Saeed, 2015). The 2mm void size was the minimum practical size possible to manufacture in the laboratory. In addition, full depth continuous pore was chosen to simplify the crack pattern and evaluate the influence of a full depth crack when water passed through this under dynamic loading when the surface is flooded with water. The recess area in concrete surface was filled with water to simulate water pressure under the slab when water is forced through a narrow crack (2mm) during traffic loading.

The lower end of the pore void, at the bottom of the slab, was connected to a pressure sensor, capable of measuring pressures in the 0-7 kPa range. The sensor range was based on the preliminary trials using a manometer to determine water pressure for 1Hz loading frequency (Saeed, 2015) . The sensors were connected to high-accuracy fast data acquisition device with 100 Hz sampling rate. The sensor electrical output ranges from 0-16.7 mV/V for pressure in range of 0- 6.89476 kPa. The sensor employed in this study excludes atmospheric pressure (101kPa). The schematic diagram and picture of test set-up is shown in Figures 4a and 4b.

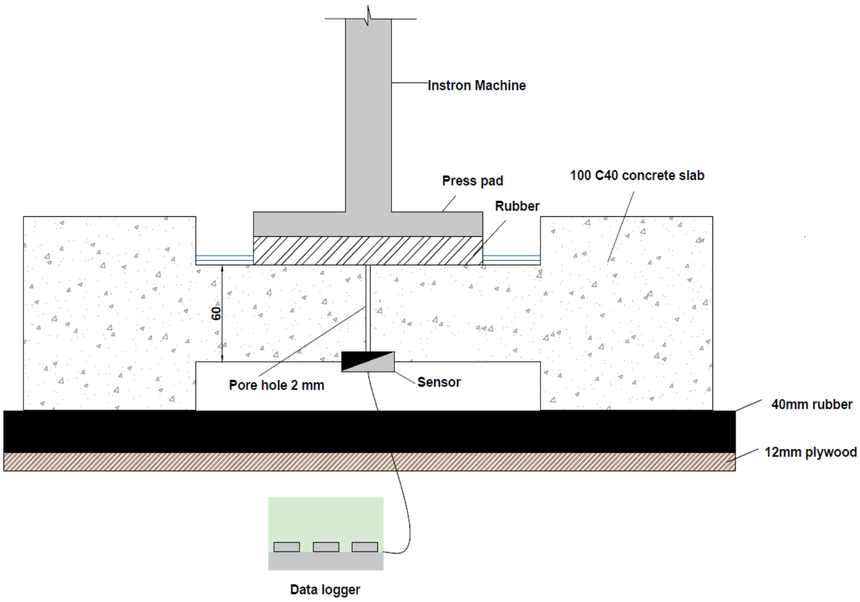


Figure 4a Schematic diagram of test setup

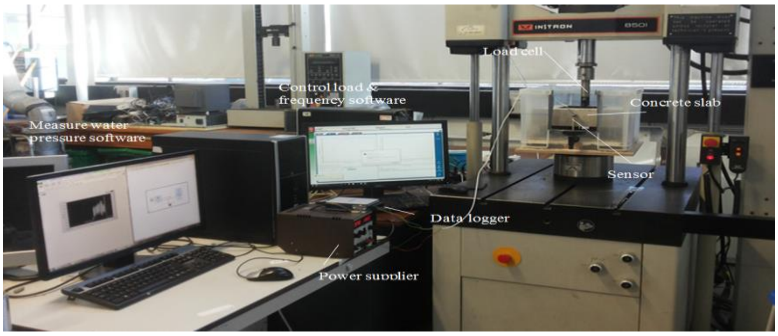


Figure 4b. Test set-up.

5. Test Specification

The test performed in this project is a non-destructive method for measuring pore water pressure under asphalt concrete. It was suitable for this project, as it can apply a repeated sinusoidal vertical load. This would be a reasonable reproduction of the on-field conditions of a load generated by the traffic load. This is a controlled stress type test in which the magnitude of the applied stress pulse is maintained constant for the required number of cycles. Therefore, the principle of this testing is that a specimen is exposed to repeated sinusoidal compressive load, developing a relatively uniform tensile stress both perpendicular and parallel to the direction of the applied load.

The testing was conducted using an INSTRON 8501 servo-hydraulic testing rig, capable of applying loads at 0.1Hz to 50Hz in the 1kN to 100 kN load range. Testing was operated in a controlled load/stress mode. The test consists of running the equipment at a required load for a given frequency and water depth, recording the resulting amplitude of water pressure under the slab. By repeating the test on each tread enables the influence of tread shapes to be evaluated. There were some variations in the water pressure measurement. This was due to the difficulty of maintaining constant level of surface water during load application.

Each test case was repeated for three times to check the repeatability and reproducibility. The test specifications are given in Table 1 and the flow chart of test sequence and testing programme is given in Figure 6**.**

Table 1. Test specifications

Variable	Specifications
Surface water depth (mm)	2, 4
Tyre Tread Type	Square, Slot
Number of tread	7
Tread Depth	0, 1.5, 3 and 8mm
Load (KN)	5, 10
Loading Frequency (Hz)	1, 5, 10 and 15
Type of Load	Dynamic Compression
Load Duration (Sec)	0.67-10
Sampling Rate	100 Hz

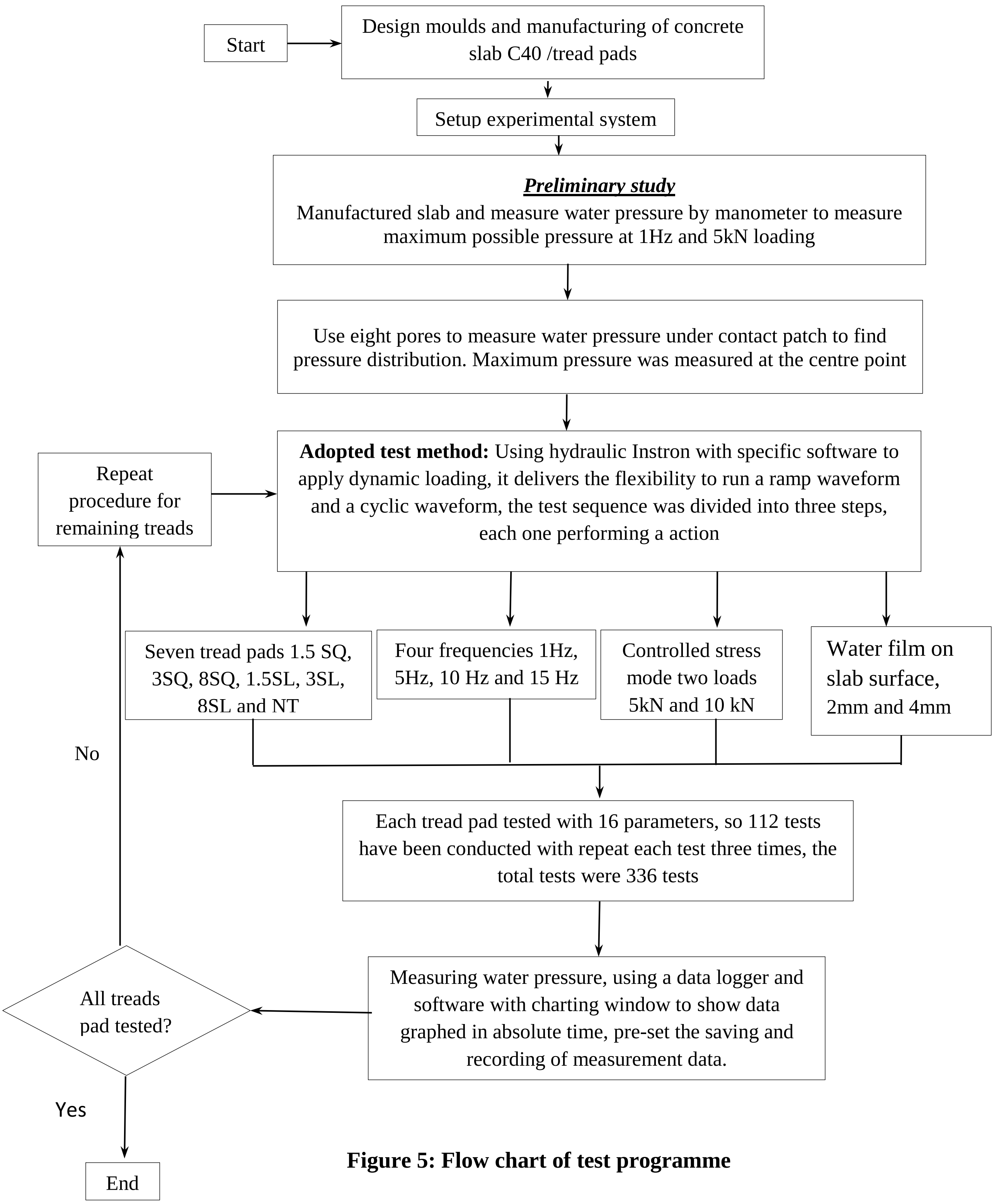


Figure 5: Flow chart of test programme

6. Results

The result section contains two parts. In part 1, the repeatability and reproducibility of the test are discussed. In part 2, the results are analysed in terms of the influence of tyre characteristics, load magnitude, load frequency and depth of surface water on the pore water pressure. The summary of the test results for different test configurations is shown in Table 2. These results are utilised to analysed the influence of different parameters as mentioned above.

Table 2. Test results

Test No	ID	Frequency	MAX				MIN				STDEVA			
			Water Depth 4mm		Water Depth 2mm		Water Depth 4mm		Water Depth 2mm		Water Depth 4mm		Water Depth 2mm	
			5KN	10KN	5KN	10KN	5KN	10KN	5KN	10KN	5KN	10KN	5KN	10KN
1-4	1.5 SQ	1HZ	2.234	3.700	2.702	3.710	2.180	3.559	2.645	3.559	0.029	0.079	0.028	0.075
5-8	1.5 SQ	5HZ	3.858	4.577	2.793	3.822	3.747	4.321	2.730	3.718	0.059	0.128	0.033	0.053
9-12	1.5 SQ	10HZ	3.732	4.857	3.242	4.907	3.600	4.756	3.149	4.775	0.076	0.051	0.050	0.066
13-16	1.5 SQ	15HZ	4.422	5.133	4.894	5.213	4.301	4.985	4.870	5.042	0.063	0.079	0.014	0.093
17-20	3 SQ	1HZ	3.080	4.662	3.029	3.150	2.991	4.528	2.946	3.015	0.048	0.072	0.046	0.078
21-24	3SQ	5HZ	4.266	5.294	3.943	5.390	4.172	5.161	3.866	5.215	0.048	0.067	0.042	0.095
25-28	3 SQ	10HZ	4.713	5.431	4.693	5.399	4.578	5.309	4.576	5.390	0.070	0.069	0.059	0.004
29-32	3SQ	15HZ	3.900	4.877	5.371	5.921	3.796	4.765	5.330	5.702	0.059	0.060	0.022	0.115
33-36	8SQ	1HZ	3.825	5.843	2.851	3.895	3.754	5.685	2.796	3.783	0.039	0.089	0.031	0.056
37-40	8SQ	5HZ	4.652	5.556	4.725	5.433	4.558	5.454	4.601	5.240	0.050	0.055	0.066	0.096
41-44	8SQ	10HZ	5.431	5.968	5.861	6.214	5.329	5.865	5.793	5.932	0.056	0.057	0.037	0.147
45-48	8SQ	15HZ	6.383	6.839	6.234	6.773	6.199	6.596	6.125	6.585	0.097	0.127	0.055	0.094
49-52	1.5SL	1HZ	2.790	3.603	2.728	3.690	2.729	3.519	2.642	3.559	0.031	0.043	0.046	0.069
53-56	1.5SL	5HZ	2.225	3.773	2.779	3.844	2.185	3.676	2.755	3.714	0.022	0.050	0.012	0.070
57-60	1.5SL	10HZ	3.715	4.882	3.252	4.867	3.599	4.741	3.151	4.763	0.063	0.077	0.058	0.058
61-64	1.5SL	15HZ	4.403	5.091	4.957	5.209	4.321	4.985	4.848	5.042	0.047	0.056	0.063	0.092
65-68	3SL	1HZ	2.104	4.649	1.863	2.128	2.043	4.528	1.753	2.066	0.032	0.061	0.059	0.031
69-72	3SL	5HZ	2.362	3.402	1.932	3.390	2.294	3.325	1.903	3.290	0.035	0.039	0.015	0.051
73-76	3SL	10HZ	2.504	5.146	1.993	5.249	2.422	4.798	1.940	4.679	0.041	0.201	0.027	0.285
77-80	3SL	15HZ	2.791	5.425	2.276	5.413	2.729	5.269	2.228	5.303	0.031	0.087	0.025	0.061
81-84	8SL	1HZ	3.023	3.591	2.245	3.604	2.939	3.493	2.200	3.524	0.045	0.051	0.023	0.044
85-88	8SL	5HZ	2.820	4.363	2.515	4.341	2.758	4.271	2.441	4.232	0.032	0.047	0.037	0.055
89-92	8SL	10HZ	3.399	5.106	3.390	5.044	3.332	4.802	3.311	4.834	0.037	0.174	0.040	0.111
93-96	8SL	15HZ	4.232	5.225	3.711	5.467	4.214	5.131	3.614	5.319	0.009	0.051	0.049	0.082
97-100	NT	1HZ	1.315	1.333	0.692	1.303	1.272	1.285	0.672	1.275	0.022	0.025	0.012	0.016
101-104	NT	5HZ	1.346	1.377	0.894	1.361	1.308	1.335	0.866	1.323	0.020	0.024	0.016	0.020
105-108	NT	10HZ	1.544	1.629	1.008	1.507	1.496	1.582	0.974	1.473	0.025	0.024	0.020	0.017
109-112	NT	15HZ	1.618	1.690	1.102	1.588	1.581	1.651	1.024	1.534	0.019	0.021	0.041	0.027

Part 1: Repeatability and reproducibility

The dynamic pressure was formed while the film of water on slab surface was pressured using load device. Positive pressure was generated in the pore along the asphalt concrete. A typical signal output at 1Hz and 5kN test configuration is given in Figure 7.

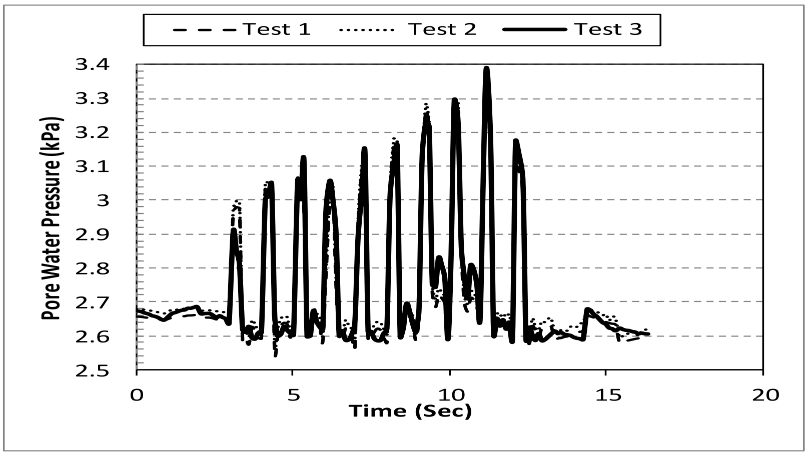


Figure 6: Pore water Pressure signal at 1 Hz and 5kN

For each test configuration, three tests were performed to evaluate the repeatability of the test. It can be seen in Figure 6 that the results are within 5%, which is indicative of good repeatability of the adopted method. After completing the first series of test, the same test configuration was repeated with different sensor to measure water pressure. The degree of agreement was found within 5% range. This indicates good reproducibility of the test method.

Part 2: Influence of tyre characterises, load magnitude, load frequency and depth of surface water
The maximum water pressure data at each test configuration from Table 2 has been plotted and is presented in Figures 8a to 8d.

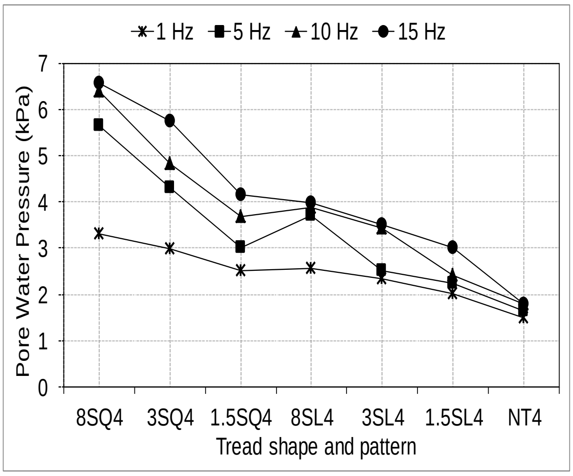


Figure 8a. 4mm surface water and load 5kN

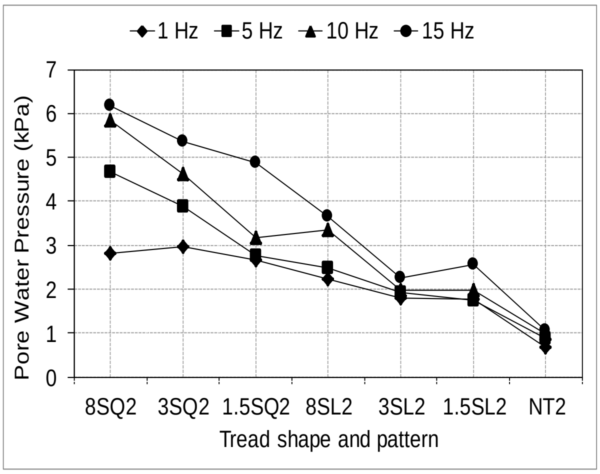


Figure 8b. 2mm surface water and 5 kN load

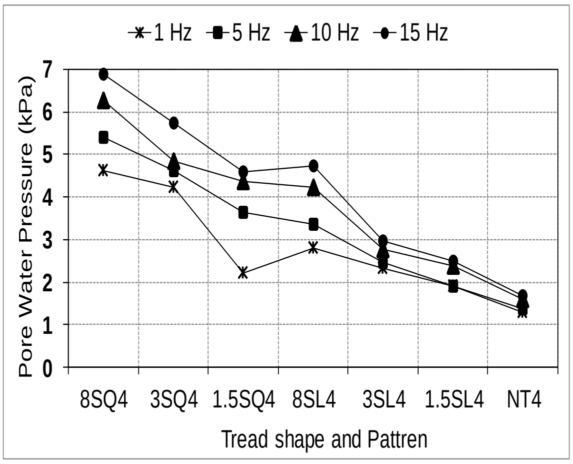


***Figure 8c*.**4mm surface water and10kN load

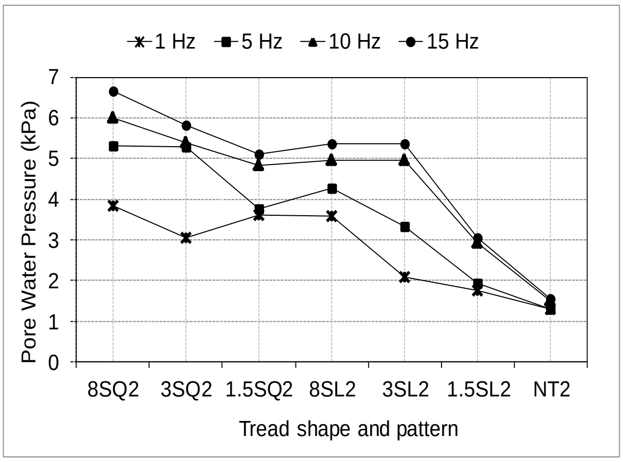


***Figure* 8d**. 2mm surface water and 10kN load

Tyre characteristics
It can be seen in Table 2 and in Figures 8a-8d, in general, at a specific frequency, irrespective of applied load, the maximum water pressure was occurred with the 8mm square tread (8SQ4) whilst the pressure decreases with decreasing tread depth, reaching minimum at the no tread situation. It is interesting to note that the water pressure in the No-tread (NT) scenario is the minimum and no change happens despite increasing either load frequency or load magnitude

Load magnitude
As with surface water, the magnitude of load appears to have only marginal influence on the pore water pressure at in all tread shape, tread patterns and loading frequency, showing only marginal increase (3%-10%) between 5kN and 10 kN load and between 4mm and 2mm depth of surface water.

Load frequency
Irrespective of surface water depth and load magnitude, the water pressure increases with increasing frequency. The water pressure decreases as tread depth decreases. As expected, for a specific frequency, water pressure is higher in a square tread than slot cut tread shape as more water is possible to drain out during the load pulse. It is interesting to note that irrespective of loading frequency, change in water pressure on flat loading plate; i.g no tread depth (NT).

Influence of surface water
From observation, the water depth 2mm and 4mm tend to have a marginal impact on increase water pressure in high frequency while is negligible at low frequencies specifically with 1.5SL and NT.

7. Summary and conclusions

The pore water pressures were measured through a 2mm representative crack underneath a 100mm concrete slab by repetitive vertical loads applied at different frequencies. The loading plate contains different tread shapes and treads patterns to represent tyre characteristics. The key conclusions are listed below

- Increasing loading frequency increases pore water in the pavement. However, water pressure increases significantly when high frequency loading combined with square types of tread with 8mm depth. This is because water was trapped inside the groove.
- Load magnitude has marginal impact on the water pressure in the concrete pavement.
- The magnitude of the water pressure is only around 7kPa, but water entrapped within the pavement voids and the joint lead to pore water pressure built up due to repeated traffic loads ultimately lead to the degradation of adhesive or cohesive which the reasons behind pavement deterioration.
- There is no significant impact of water depth on increase of water pressure when combined with low frequencies specifically with 1.5 SL and NT. It has marginal impact at high frequencies.

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